Development of an *in situ* peak intensity measurement method for ultraintense single shot laser-plasma experiments at the Sandia *Z* petawatt facility

Anthony Link, Enam A. Chowdhury, John T. Morrison, Vladimir M. Ovchinnikov, Dustin Offermann, Linn Van Woerkom, and Richard R. Freeman
The Ohio State University, 191 West Woodruff Avenue, Columbus, Ohio 43210

John Pasley, Erik Shipton, and Farhat Beg
University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093-0411

Patrick Rambo, Jens Schwarz, Matthias Geissel, Aaron Edens, and John L. Porter
Sandia National Laboratories, P.O. Box 5800, MS 1193, Albuquerque, New Mexico 87185-1193

(Received 9 May 2006; presented on 9 May 2006; accepted 11 July 2006; published online 19 October 2006)

Using the physical process of ultraintense field ionization of high charge states of inert gas ions, we have developed a method of peak intensity measurement at the focus of high energy short pulse lasers operating in single shot mode. The technique involves detecting ionization products created from a low pressure gas target at the laser focus via time of flight detector. The observation of high ion charge states collected by the detector yields peak intensity at the focus when compared with the results obtained from well established tunnel ionization models. An initial peak intensity measurement of 5×10^{16} W cm^{-2} was obtained for a 1.053 μm center wavelength, 0.4 J pulse with 1 ps pulse duration focused with an $f/5.5$ off-axis parabola. Experiments with multijoule level, 500 fs laser pulses are on the way. © *2006 American Institute of Physics.*
[DOI: 10.1063/1.2336469]

INTRODUCTION

Peak intensity at the laser focus is one of the crucial parameters in high energy density physics (HEDP) experiments based on ultraintense laser solid interaction. The nature of highly nonlinear coupling between the laser field and target electrons depends on the focal intensity,[1] which then determines electron transport through the target and other related mechanisms such as energetic proton generation. It is also known that fast ignition inertial confinement fusion (FI-ICF) requires some threshold intensity at the focus to generate fast electrons/protons.[2] It is, however, not well understood at what intensity the process is optimized. Accurate peak intensity information is also required for numerical simulation of such complex processes to explain experimental observations and guide experimental efforts. However, to our knowledge, none of the large facilities currently operational (Vulcan at RAL, Titan at LLNL, Gekko/FIREX in ILE, etc.) have direct intensity measurement capabilities, and intensity is estimated from indirect measurements—which involve measuring the focal spot size and determining the energy content in it, in addition to measuring the temporal profile of the pulse with one of several autocorrelation methods. It is usually not feasible to perform the focal spot measurement with fully amplified pulse. So, a partially amplified beam is used instead (with a small percentage of its light being picked up by the front surface of a highly transmissive optic) for the measurement. With fully amplified light, more wave front distortions come into play due to the nonuniform thermal lensing effect at the gain media. The focusing element, usually an off-axis parabola (OAP), is difficult to align, and furthermore, surface aberrations/imperfections in it may cause drastic distortion of the focal spot. Also, on the temporal profile aspect, one shot pulse-width measurements are not yet available in most large facilities. Indirect temporal width estimation from pulse spectrum assuming a transform limited pulse may be off by an order of magnitude due to imperfections in compressor gratings or sizable accumulation of the B integral as the ultrashort high power pulse traverses different media before arriving at the focus.[3] That is why it is in general difficult to infer *real peak intensity at the focus* from indirect measurements. So, an *in situ* measurement of peak intensity at the focus of an ultraintense pulse is extremely important. In this article, we report, for the first time, the installation and preliminary experimental run of such an *in situ* peak intensity calibration system at the *Z* petawatt laser facility at the Sandia National Laboratories.

METHOD

Peak intensity at the laser focus can be directly ascertained by observing ionization of highly charged ions at the focus. Precision measurements of high field ionization of inert gases[4,5] with simultaneous semiclassical modeling and numerical solutions of full three-dimensional (3D) time dependent Schrödinger equation[6] have established the reliability of using these charge states as an effective gauge of intensity calibration at high intensities. As it was shown by Chowdhury *et al.*,[7] semiclassical tunnel ionization rates are adequate to explain ionization of charge states (with bound

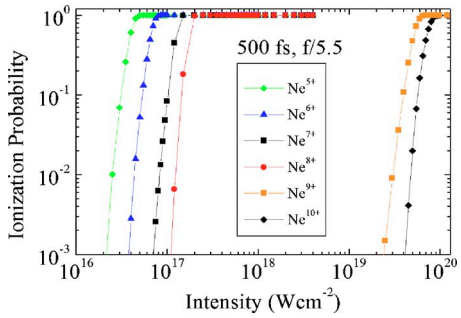

FIG. 1. Neon tunnel ionization probability in a 500 fs, $f/5.5$ focus with 1.05 μm laser pulse.

energies up to a few keV) with ultraintense lasers. In this method of determining peak intensity at the focus, usually multiple shots are required to collect enough statistics and high dynamic range. Most laser systems that are used are in the peak power range of multiterawatt or less and operating at 10 Hz or higher repetition rate. However, single shot intensity calibration is possible, since the probability of tunnel ionization has approximately I^5 dependence below saturation (ionization probability of $1/e$), and highest peak intensity is confined to very small focal volume. [For example, at 10^{-4} torr pressure in the 193 μm^3 (5 μm spot) volume confined by the isointensity surface at half-peak intensity, there would be 800 Ne atoms present. At 1×10^{20} W cm^{-2} Ne^{10+} would have unity probability of ionization, as shown in Fig. 1. With a 50% detection efficiency (typical), 400 of these Ne^{10+} ions would be detected in a single shot]. Detection of highest ionization charge state of a species and nondetection of next highest charge state essentially impose a lower and an upper bound on peak intensity, when the measurement is performed with a highly efficient detection system. Such detection systems have allowed highest dynamic range ionization yield measurements in ultraintense fields over decades of intensity range.[8] Recent measurements of field ionization of high charge states of Xe and Kr in JAERI 100 TW system have also demonstrated feasibility of using such a system to measure peak intensities around 10^{20} W/cm^2.[9]

DESCRIPTION OF EXPERIMENT

The Z petawatt (ZPW) laser architecture is based on a three stage amplification system consisting of an optical parametric chirp pulse amplifier (OPCPA), a pair of glass rod amplifiers, and several high power slab amplifiers. Amplified pulses with a center wavelength of 1.053 μm then enter a vacuum compressor capable of delivering 100 J/pulse with 500 fs pulse duration. As the ZPW laser facility is still under construction and shot accessibility is limited, our strategy involved installing two nearly identical experimental setups, one at the petawatt laser facility and another at the Ohio State University (OSU) 1 TW laser laboratory, where a 90 fs, 90 mJ Ti:sapphire chirp pulse amplifier (CPA) laser operates at 800 nm with 10 Hz repetition rate, but also can be run at single shot mode. This way, between the shot runs at ZPW, the OSU facility can act as a test bed for planning and troubleshooting experiments.

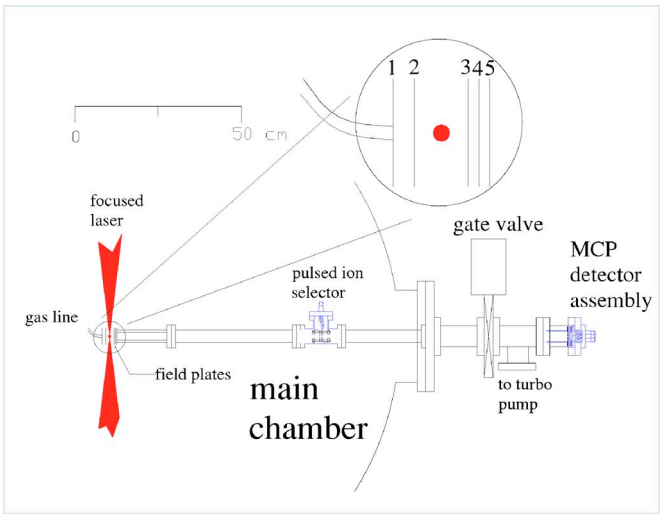

FIG. 2. Setup of TOF assembly setup at Sandia National Laboratory target chamber. The inset shows the gas jet and field plate assembly in more detail.

In Fig. 2, a schematic of the time of flight (TOF) detector assembly setup at ZPW is shown, which is specially designed to detect highly charged ionization states of various inert gas species (Ne, Ar, Kr, Xe, etc.). The ion detector flight tube with field plate assembly (plates 1–5 in inset of Fig. 2 are precision aligned with one another with a 500 μm diameter center hole on each) is attached to the main chamber. A leak valve delivers gas to plate 1 via a stainless steel (SS) tubing attached to it whereas plate 2 acts as a skimmer for the gas jet. The laser focus is placed between plates 2 and 3 and aligned by crossing it with an alignment laser beam (placed at the detector end of TOF tube) coming through center holes in plates 3–5. This assembly ensures that the gas jet, laser focus, and multichannel plate (MCP) (25 mm chevron MCP from Burle) detector are all aligned together. A 2–2.5 kV potential drop from plate 2 to plate 3 accelerates the ions past the interaction region into the flight tube. The relatively high potential difference ensures minimization of space charge effects on the high charge state ion trajectories. This type of setup has been successfully used previously to collect virtually noiseless data with target gas pressures exceeding 10^{-4} torr.[8,10] Differential pumping ensures that the base pressure at the detector assembly is at 10^{-8} torr level (or below as the main chamber base pressure varies between 3×10^{-7} and 5×10^{-6} torr) and the gate valve keeps it under vacuum when the main chamber is vented. The key in designing the detection setup is to set the timing of the pulsed ion selector consisting of three annular plates with wire mesh covered center holes, where the outer plates are grounded and the center plate is attached to a high voltage pulser (DEI PVM-4210). Using a digital delay generator (SRS DG 535) synchronized with the laser pulse, the selector can block the lower ion charge states which are generated in copious amounts in the large regions surrounding the focus. This protects the detector from saturation and significantly improves signal to noise ratio.

Two modes of data collection electronics were set up—one for the 10 Hz OPCPA pulses with 2 mJ/pulse compressed into the target chamber and another for single shot

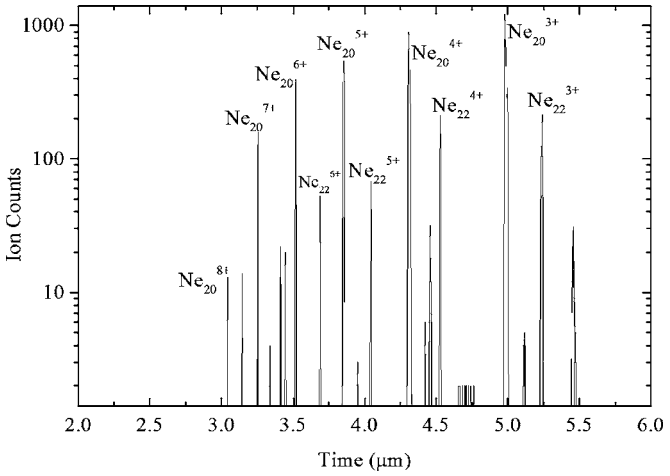

FIG. 3. OSU multishot neon TOF spectrum collected with 800 nm, 90 fs pulse with 97 mJ energy into the chamber with an $f/2.5$ focus. Data are accumulated for 22 000 shots, with chamber gas pressure of 5×10^{-7} torr.

amplified beams [400 mJ–50 J compressed before the petawatt (PW) compressor is constructed]. Multishot data were collected at low event probability (less than 0.2 ions/shot) with a fast preamplifier (Ortek model 9306) connected to a fast timing discriminator (Ortek model 9307), which digitizes the signal for a picosecond time analyzer (Ortek model 9308). Single shot data were collected via a 10 GHz digital oscilloscope (Tektronix). All the signal cables were shielded and collection electronics and a computer were placed in a Faraday cage to protect them from electromagnetic pulses (EMPs) generated by the PW system.

DISCUSSION AND ANALYSIS

Multishot spectrum collected at OSU (shown in Fig. 3) presents nearly noise-free data, even with the whole neon outer shell stripped with 97 mJ, 90 fs pulses. The chamber base pressure was 10^{-8} torr, and pressure with target gas in the chamber was 3×10^{-7} torr. The pulsed ion selector was used here to block ion charge states Ne^{+} and Ne^{2+}. The calibrated intensity by comparing ratios of theoretical ionization yields versus experimental yields results in $(2.5\pm1.0)\times10^{17}$ W cm^{-2} peak intensity at the focus. Single shot measurements were also performed with the same laser observing up to Ne^{6+} consistently. Ne^{7} or Ne^{8+} ions were not observed due to low event probability.

The base/target pressure at the Sandia target chamber was $7\times10^{-6}/1.2\times10^{-5}$ torr. The experimental run began in multishot mode with 2 mJ OPCPA pulses compressed to 0.5–1.0 ps. A sample single shot OPCPA data is shown in Fig. 4(a) where all the Kr^{+} isotopes are present along with some background ion signals. This method was used to align the focus with the ion collection holes by maximizing Kr^{+} signal, and then the laser was run in single shot mode to determine the time window and triggering offset at the oscilloscope using H^{+} and Kr^{+} ion signals. Neon could not be used because the pulse intensity was inadequate to ionize it.

The rod amplifier shot data were collected with a total of 14 shots with energies ranging from 300 to 400 mJ and pulse duration of 0.5–1.0 ps within a span of 2 days. This was the

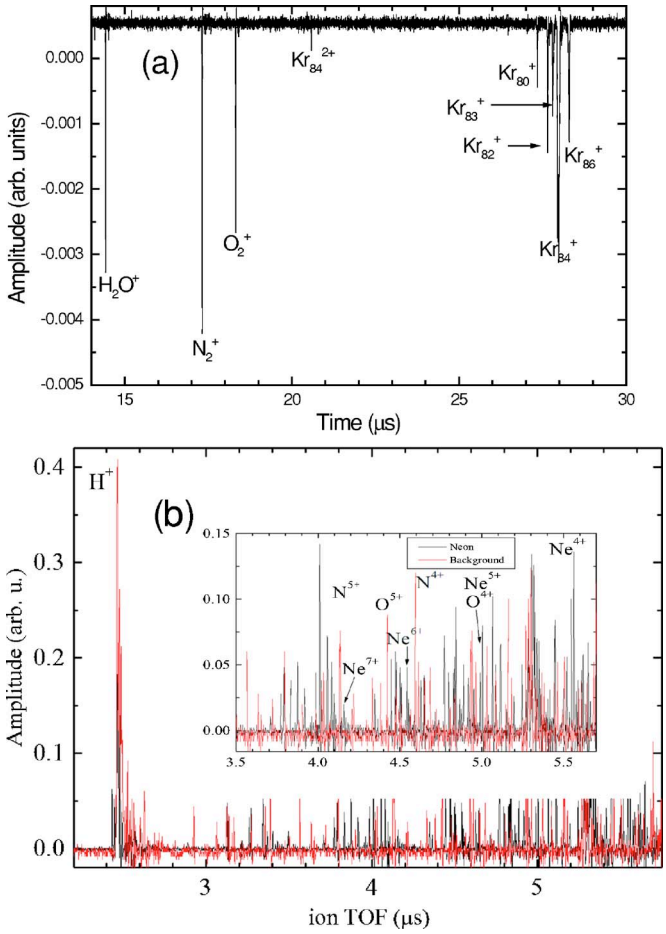

FIG. 4. (a) Single shot ion TOF spectrum collected with 2 mJ unamplified OPCPA beam with pulse duration of 0.5–1.0 ps and a 10 μm focal spot, with Kr as sample gas. (b) Single shot ion TOF spectra (background in solid red and target gas neon in solid black) with 0.4 J pulse with pulse duration of 0.5–1.0 ps. Inset shows region of interest with specific ion peaks [total chamber pressure of 1.2×10^{-5} torr with target gas for both shots (a) and (b)].

first experimental run using the Sandia ZPW laser system. A few spectra were collected with background gas as target, to compare with the neon gas signal. Target gas was delivered by a 63 mm bypass nozzle (connected to a needle valve) placed 25 mm away from focus, because both the gas jet and the ultrahigh vacuum leak valve were clogged. Ions were swept away with 2.5 kV potential difference between plates 2 and 3, and the MCP was biased at −1.8 kV. The pulsed ion selector was not used in this shot run because the high voltage pulser was not available. A sample shot TOF spectrum is shown in Fig. 4(b) with a background shot data for comparison. Compared to the OPCPA data taken with the same setup, the signal to noise ratio is poorer. However, the clear presence of H^{+} peaks in both background and target gas shots and various other background ion peaks help identify neon charge states in the vicinity. Also, we note that the background peaks are wider than signal peaks and almost every background peak is suppressed in the neon spectrum due to higher target gas density. Based on the presence (and saturation) of Ne^{4+}–Ne^{6+} and possibly Ne^{7+}, the peak intensity is estimated from field ionization probability and focal volume integrated yield calculations (part of which is shown

in Fig. 1) to be 5×10^{16} W cm^{-2} with a 50% accuracy, which takes into account the pulse-width jitter between 0.5 and 1.0 ps. This corresponds well with the indirect peak intensity estimate of 5.7×10^{16} W cm^{-2} based on indirect method assuming the 400 mJ pulse was focused to a 30 μm spot with 1 ps pulse duration.

It is clear from the inset of Fig. 4(b) that an ion signal peak from any given ion species was broken up into multiple peaks, indicating that experimental parameters had significantly changed in the amplified rod shot from that of the low energy OPCPA shots. EMP coupling to the MCP was ruled out when it was observed that the ion signals disappeared when the ion path to the MCP was blocked with the gate valve closed. Although some thermal lensing correction was incorporated in the amplifier system, a considerable amount of on shot residual thermal lensing was still present in the laser system. This effect most probably contributed to the misalignment and degradation of the focus of the amplified beam with respect to that of the OPCPA beam. The degraded focus with a much larger effective volume then could create a massive envelope of lower ion charge states whose effect would worsen in the absence of a gas jet (which keeps the gas atoms confined to relatively smaller volume). The high ion charge states created at the center (most intense part) of this envelope would then have to traverse a longer path through the charge clouds (space charge Coulomb force increases linearly with radius of a uniform charge cloud), which possibly caused the ion bunches to be defocused, so that they arrived at the detector as separate sub-bunches within tens of nanoseconds, resulting in multiple peaks per charge species in the TOF spectra.

FUTURE PLANS

To correct the thermal lensing in the amplifier system, deformable mirrors have been installed and tested. Shot to shot pulse duration and energy fluctuations have been minimized and the Sandia ZPW front end laser is nearly ready to fire 10–50 J amplified shots. The second phase of this experiment is expected to be arranged within a few months.

In conclusion, a new method of *in situ* peak intensity measurement is introduced in a large scale ultraintense laser facility. The ion collection method is shown to operate well in multishot mode and single shot mode with unamplified OPCPA pulses. The Sandia ZPW front end amplified laser peak focal intensity calibration has been found to be $(1.25\pm0.75)\times10^{14}$ W cm^{-2} per millijoule energy. The reason for degradation of ion signal in amplified pulse has been identified to be an enhanced space charge effect due to the thermal lensing degradation of the target focus.

[1] S. Atzeni, Phys. Plasmas **6**, 3316 (1999).
[2] R. R. Freeman *et al.*, Eur. Phys. J. D **26**, 73 (2003).
[3] E. Chowdhury, Ph.D. thesis, University of Delaware, 2004.
[4] B. Walker, B. Sheehy, L. F. DiMauro, P. Agostini, K. J. Schafer, and K. C. Kulander, Phys. Rev. Lett. **73**, 1227 (1994).
[5] A. Talebpour, C-Y Chien, Y. Liangz, S. Larochelle, and S. L. Chin, J. Phys. B **30**, 1721 (1997).
[6] H. G. Muller, Opt. Express **8**, 417 (2001).
[7] E. A. Chowdhury, C. P. J. Barty, and B. C. Walker, Phys. Rev. A **63**, 042712 (2001).
[8] S. Palaniyappan, A. DiChiara, E. Chowdhury, A. Falkowski, G. Ongadi, E. L. Huskins, and B. C. Walker, Phys. Rev. Lett. **94**, 243003 (2005).
[9] Y. Akahane *et al.*, Rev. Sci. Instrum. **77**, 023102 (2006).
[10] E. Chowdhury and B. Waker, J. Opt. Soc. Am. B **20**, 109 (2003).